FIELD–ALIGNED ELECTRIC FIELD IN THE IO FLUX TUBE AS A RESULT OF A PRESSURE PULSE NEAR IO

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Abstract

Pressure pulses produced near Io by volcanic outbursts or created in the course of torus plasma flow around Io, eventually generate slow shocks accompanied by a supersonic flow behind the shock. It is known that a supersonic flow produces a field–aligned electric field [Serizava and Sato, 1984]. It is a fact that if the mass velocity of ions is much bigger than the thermal velocity (supersonic flow), then the most part of the ions must have small pitch angles, whereas the electrons, for which the thermal velocity is much larger, should not be noticeably disturbed. As a result, the mirror points of the streaming protons and electrons are located at different positions along the Io flux tube leading to a charge separation and the occurrence of a field–aligned electric field. The method of Serizava and Sato modified for the Io flux tube with its very special types of ions has been used to calculate the potential difference, which can be as large as several kV for sufficiently strong pressure pulses.

Introduction

The interaction of Io with the magnetosphere of Jupiter has been, and continues to be, a subject of intense interest in space plasma physics. In most descriptions of the Io interaction, the motion of Io through the corotating magnetosphere results in the generation of Alfvèn waves propagating away from Io into the magnetospheric plasma [Neubauer, 1980]. However, we concentrate on a mechanism connected with the slow mode acting along the Io flux tube. A possible generation of a slow mode wave at the position of Io is given by Io's high volcanic activity, or by the plasma flow past Io [Linker et al., 1991]. The

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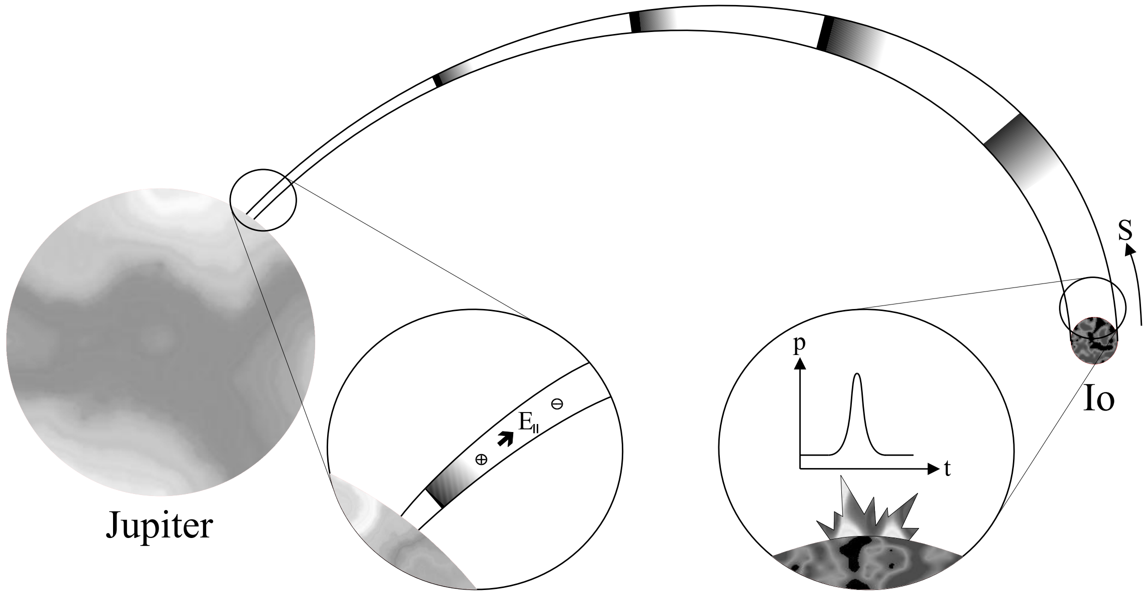

Figure 1: Sketch of the geometry and basic assumptions applied to the stated problem.

slow mode waves are converted into slow shocks accompanied by an accelerated plasma flow. Following these slow shocks towards Jupiter, reveals that the flow velocity increases towards Jupiter along the magnetic tube up to values of the initial Alfvèn velocity at Io. The reason for this enhancement stems from the narrowing of the flux tube together with the increase in the amount of the Jovian magnetic field. Due to this strong plasma flow, the different plasma contributions, i.e., electrons and ions, mirror at different points and thus, a charge separation develops along the magnetic field, which in turn leads to the generation of an electric potential difference. The aim of the present paper is to estimate this potential drop, thereby applying well–known methods of kinetic theory following the method of Serizava and Sato [1984].

The main idea of how the potential difference is calculated is sketched in Figure 1. As a starting point, we take the plasma flow to be directed along the magnetic field towards Jupiter. At the location of this plasma flow, namely at the source point, we assume quasi–neutrality, i.e., $n_{e,0} = \sum n_{i,p,0}$, where n_e, n_i, p, and 0 denote electron particle number, ion particle number, species of ions, and quantities at the source point, respectively. As a next step, we assume that all plasma contributions have the same bulk velocity, V_0. From these two basic assumptions, we directly conclude that at the source point the electron flux, $F_{e,0}$, has to be equal to the sum of the respective ion fluxes, $F_{i,p,0}$. Assuming that there is no current present and, in addition, mass conservation along the magnetic flux tube, yields that the reflected electron flux is equal to flux carried by the reflected ion populations. This equality allows one to obtain the electric potential difference as a function of the distance, s, measured along the flux tube.

Basic equations

At the source point we assume the particles to be distributed according to a so–called parallel beam distribution function given as

$$\begin{aligned} f(v_{\|,j}, v_{\perp,j}^2) &= \frac{n_j}{T_{\perp,j} T_{\|,j}^{\frac{1}{2}}} \left(\frac{m_j}{2\pi}\right)^{\frac{3}{2}} \exp\left(-\frac{m_j v_{\perp,j}^2}{2T_{\perp,j}}\right) \left[\exp\left(-\frac{m_j}{2T_{\|,j}}(v_{\|,j} - V_0)^2\right)\right. \\ &\quad \left. - \exp\left(-\frac{m_j}{2T_{\|,j}}(v_{\|,j} + V_0)^2\right)\right], \end{aligned} \tag{1}$$

where n, m, v, and T refer to particle number, mass, microscopic velocity, and temperature in energy units, respectively. Subscript j denotes the particle species and subscripts $\|$ and $\perp$ characterize the components of the relevant quantities parallel and normal with respect to the magnetic field, which we approximate by using a dipole configuration.

In order to calculate the reflected flux we apply the concept of moments of the distribution function. Since we are interested in the reflected contribution, the integral over the microscopic velocities is taken over a particular region in the respective velocity space. These regions are determined by the conservation of energy and the conservation of magnetic momentum. Combining these two conservation relations allows us to obtain the following expression for the particles parallel velocity

$$v_{\|,j}^2 = v_{\|0,j}^2 - \left(\frac{\sqrt{1 + 3\sin^2\lambda}}{\cos^6\lambda} - 1\right) v_{\perp 0,j}^2 - \frac{2\, q_j}{m_j}\Phi. \tag{2}$$

Here, Φ denotes the electric potential difference, which is initially zero, q refers to the charge, and λ corresponds to the magnetic latitude. At the particles mirror points their parallel velocity component vanishes. Thus, the right–hand side of equation (2) determines a curve in the velocity space, which separates the reflecting contribution from the passing. The shape of the curve in the electron and ion velocity space is shown in Figure 2. As a next step, we derive the explicit expressions for the reflected fluxes, $\mathcal{F}_s$, by calculating the first moment of the distribution function over the relevant regions. The result is as follows

$$\mathcal{F}_e = n_{0,e} V_0 \left(\frac{(\gamma-1)T_{\perp,e}}{\left(T_{\|,e} + (\gamma-1)T_{\perp,e}\right)}\right)^{\frac{3}{2}} \exp\left(-\frac{m_e}{2}\frac{V_0^2}{(\gamma-1)T_{\perp,e} + T_{\|,e}} - \frac{q_e \Phi}{(\gamma-1)T_{\perp,e}}\right), \tag{3}$$

$$\begin{aligned} \mathcal{F}_i &= n_{0,i} V_0 \left[\frac{1}{V_0\sqrt{2\pi m_i}} \frac{T_{\|,i}^{\frac{3}{2}}}{T_{\|,i} + (\gamma-1)T_{\perp,i}} \left(\exp(-x_1^2) - \exp(-x_2^2)\right)\right. \\ &\quad + \frac{1}{2}\left(\mathrm{Erf}[x_1] + \mathrm{Erf}[x_2]\right) + \frac{1}{2}\left(\frac{(\gamma-1)T_{\perp,i}}{(\gamma-1)T_{\perp,i} + T_{\|,i}}\right)^{\frac{3}{2}} \\ &\quad \left. \exp\left(-\frac{m_i}{2}\frac{V_0^2}{(\gamma-1)T_{\perp,i} + T_{\|,i}} + \frac{q_i\Phi}{(\gamma-1)T_{\perp,i}}\right)\left(2 - \mathrm{Erf}[x_3] - \mathrm{Erf}[x_4]\right)\right], \end{aligned} \tag{4}$$

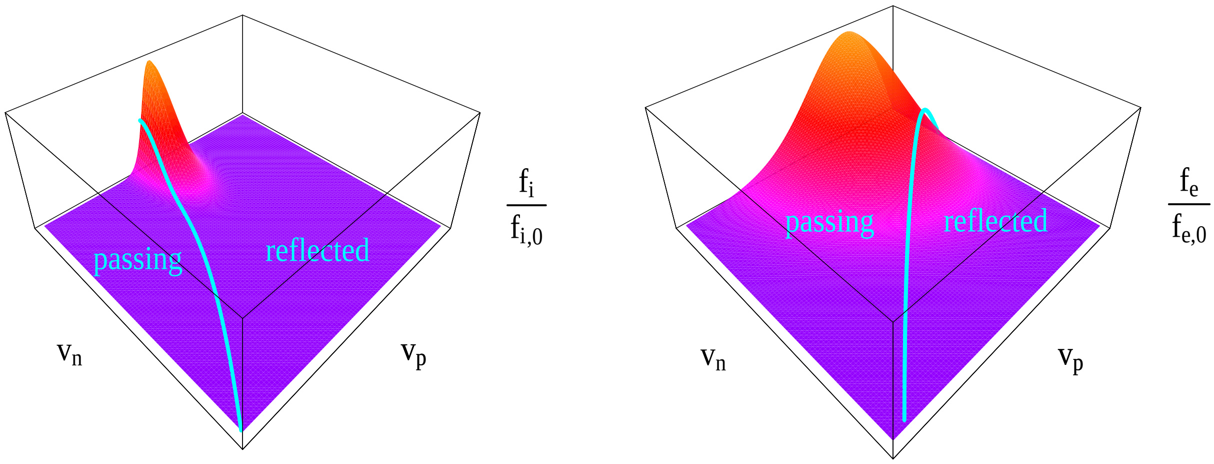

Figure 2: Sketch of the electron and ion velocity space with the respective distribution function and separation curve.

with

$$x_1 = \sqrt{\frac{m_i}{2T_{\|,i}}}\left(\sqrt{\frac{q_i\Phi}{m_i}} + V_0\right), \tag{5}$$

$$x_2 = \sqrt{\frac{m_i}{2T_{\|,i}}}\left(\sqrt{\frac{q_i\Phi}{m_i}} - V_0\right), \tag{6}$$

$$x_3 = \left(\frac{(\gamma-1)T_{\perp,i} + T_{\|,i}}{(\gamma-1)T_{\perp,i}T_{\|,i}}\right)^{\frac{1}{2}} (q_i\Phi)^{\frac{1}{2}} + \left(\frac{m_i}{2}\,\frac{(\gamma-1)T_{\perp,i}}{T_{\|,i}\left((\gamma-1)\,T_{\perp,i} + T_{\|,i}\right)}\right)^{\frac{1}{2}} V_0, \tag{7}$$

$$x_4 = \left(\frac{(\gamma-1)T_{\perp,i} + T_{\|,i}}{(\gamma-1)T_{\perp,i}T_{\|,i}}\right)^{\frac{1}{2}} (q_i\Phi)^{\frac{1}{2}} - \left(\frac{m_i}{2}\,\frac{(\gamma-1)T_{\perp,i}}{T_{\|,i}\left((\gamma-1)\,T_{\perp,i} + T_{\|,i}\right)}\right)^{\frac{1}{2}} V_0, \tag{8}$$

where γ denotes the ratio of the magnetic field normalized to the magnetic field at the source point and Erf $[x]$ is the error function. Due to the equality of the reflected particle fluxes, i.e.,

$$\mathcal{F}_e = \sum \mathcal{F}_{i,p}, \tag{9}$$

the electric potential can be calculated as a function of the distance along the flux tube.

Solution

In order to simulate the conditions in the Io flux tube, we assume the plasma stream to contain hot anisotropic ions (S^+ and O^+) with $T_{\perp,i} = 5\ T_{\|,i} = 200$ eV, and isotropic electrons with $T_{n,e} = T_{p,e} = 150$ eV [Mei et al., 1995]. We assume the source point to be located at $s = 6\ R_j$, which is just slightly more than one Jupiter radius above the

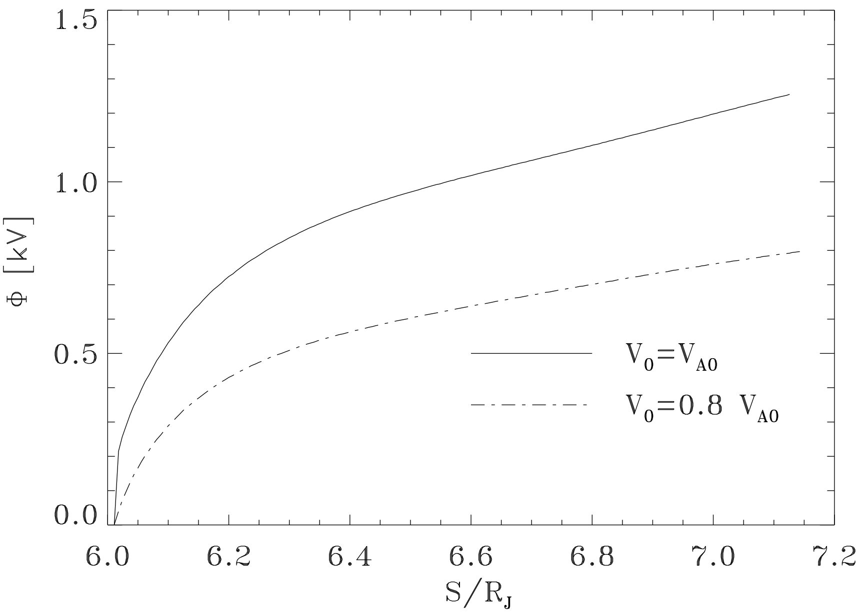

Figure 3: Profiles of the electric potential as a function of s for different initial velocities. The Alfvèn velocity at the position of Io is $V_{A0} = 250$ km/s.

planets surface. The obtained potential drop as a function of s is shown in Figure 3, where we model two plasma flows of different strength. The main result of this study is that the strength of the potential drop is directly proportional to the flow energy of the ions. Thus, a fast plasma flow leads to a strong potential (see Figure 3). Additionally, the rather heavy ions along the Io flux tube contribute to a strong potential difference.

Conclusions

In this paper we tried to emphasize the importance and application of slow mode waves with regard to the interaction of Io and Jupiter. The slow mode waves can be excited due to the Io volcanism or are created in the course of plasma flow around the satellite. The slow waves develop into slow shocks, which are propagating along the Io flux tube accompanied by a strong plasma flow behind the shock. This strong plasma flow leads to an electric potential difference along the magnetic field, which can reach values of about 1 kV. As the precipitating electrons pass the developed potential drop, they pick the potential drop's energy and are effectively accelerated. Thus, the slow mode wave scenario seems to contribute to the explanation of the excitation of aurora on Jupiter and the Jovian decameter radio emission [Wu, 1988] together with the generally accepted Alfvèn wings model [Neubauer, 1980].

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